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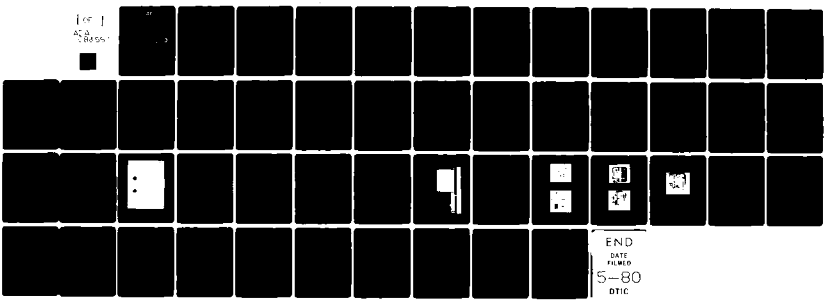

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RUDDER ROLL STABILIZATION SYSTEM USER'S GUIDE

by

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and

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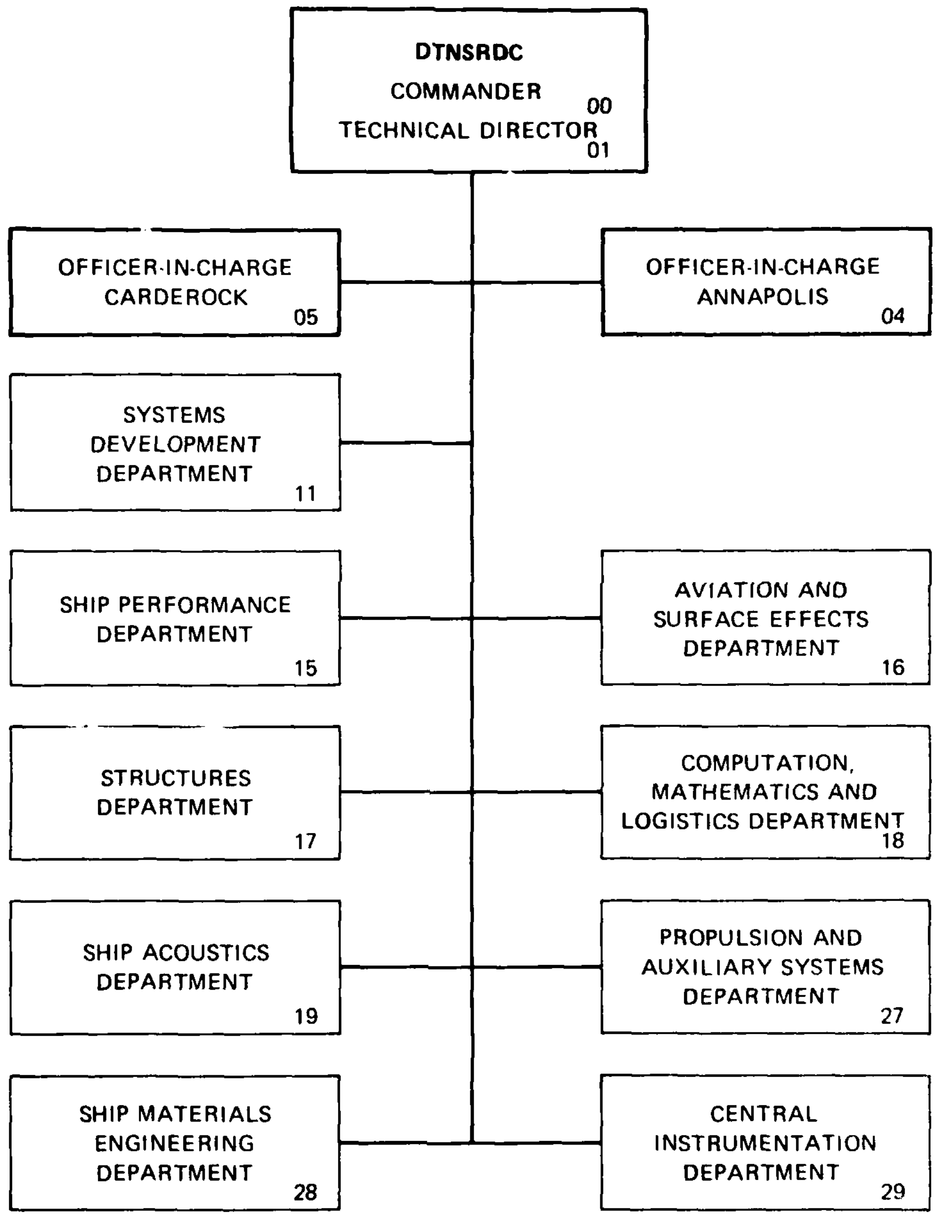

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two prototype Rudder Roll Stabilization systems were built and installed on U.S. Coast Guard WHEC cutters during 1978 and 1979. This report documents the design, fabrication, and installation of these systems and provides guidance on their use and repair. Sufficient detail is provided to enable the reader to duplicate and install a similar system on a similar vessel; however, the design considerations which optimize the system for a specific vessel class

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are treated only briefly. A subsequent David W. Taylor Naval Ship Research and Development Center report which addresses these design considerations and provides trial documentation of the system effectiveness is currently in preparation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Two prototype Rudder Roll Stabilization systems were built and installed on U.S. Coast Guard WHEC cutters during 1978 and 1979. This report documents the design, fabrication, and installation of these systems and provides guidance on their use and repair. Sufficient detail is provided to enable the reader to duplicate and install a similar system on a similar vessel; however, the design considerations which optimize the system for a specific vessel class are treated only briefly. A subsequent David W. Taylor Naval Ship Research and Development Center report which addresses these design considerations and provides trial documentation of the system effectiveness is currently in preparation.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The purpose of this publication is to provide guidance in the use of the Rudder Roll Stabilization (RRS) system installed aboard USCG cutters JARVIS (WHEC 725) and MELLON (WHEC 717) and to provide sufficient technical documentation to repair and/or duplicate these devices, if necessary. These systems are prototypes and therefore, not all possible repair/alignment procedures can be accomplished shipboard. All system components may be easily removed and transported to a location where the required test equipment is available to make proper repairs. The systems were designed to be almost maintenance free; requiring only to check, clean or replace, as necessary, one hydraulic filter.

An overview is hereby given which describes the basic function and operation of the system. A more detailed explanation is then given, followed by detailed descriptions of each component along with a discussion of the electrical, hydraulic, or mechanical operation of the unit. In this manner, the reader is able to select the degree to which he or she wishes to investigate each device or component.

RUDDER ROLL STABILIZATION SYSTEM

The RRS system attempts to reduce the rolling motion by inducing a timely rudder movement which tends to roll the ship in opposition to the roll induced by the seaway. A simplified discussion of the selection and operation of the control law used in the stabilization system is given in Appendix A.

The RRS system is composed of a helm unit, a controller, two actuators, and a rudder angle sensor, all appropriately interconnected electronically/ hydraulically/mechanically with each other and/or with the ship steering system. The helm unit is located on the bridge and is used to operate the other components located in the after steering compartment. The following sections describe these components in more detail.

HELM UNIT

1. Purpose:
   a. Turns system power off and on,
   b. Selects ship steering system or stabilizer system,
   c. Accumulates time and use data,
   d. Provides visual display lamps to indicate system status.
2. Location:
   a. MELLON - Bridge console, face, starboard or helmsman chair.
   b. JARVIS - Bridge overhead, starboard of steering motor switches.
3. Principle of Operation:

The helm unit is used to provide a helmsman rudder command signal to the stabilizer system when the system is operational (engaged). At other times normal steering operation is maintained. When the helm unit is in the "off" position, no power is applied to the stabilization system as indicated by the red panel light labeled "system power" on the left of the helm unit face plate (refer to Figure 1). In the "standby" position, power is applied to the stabilization system to allow the various electronic components to warm-up. The amber panel light, labeled "system standby," indicates that warm-up is in progress while the amber panel light labeled "system ready" indicates that sufficient warm-up time has elapsed. The switch from "system standby" to "system ready" is automatic and occurs

approximately 5 minutes after the "standby" switch setting is selected. Prior to switching the system on, the following steps should be completed:

1. Ascertain that the system hydraulic cut-off valve is open and that the system hydraulic filter is clean (see Actuator section),
2. Select the "hand" mode of steering operation,
3. Engage both (port and starboard) steering motors,
4. Allow "system ready" light to come on,
5. Select starboard steering cable.

Actual engagement (or disengagement) of the system should be made during relatively low rolling motions and with the helm near midships to facilitate change over clutching as discussed in the Actuator section. The "on" position is indicated by a green panel light labeled "system engage."

To disengage the system, merely select the "standby" position. After a few moments the system may then be turned off ("off" position) or reengaged.

Note: The JARVIS unit shown in Figure 1 is equipped with a master "on-off" switch (lower left corner of face plate) which MELLON does not have at this writing. This switch may be left in the "on" position indefinitely with no harm. It was provided to turn off the "system power" light which was found to be disturbing at night during operations aboard MELLON. The indicator lights have since been replaced by a type suitable for night use.

4. Schematic Description:

As shown in Figure 2, the RRS helm switch, S_1, is connected to provide normal ship system operation in the "off" and/or "standby" position; apply power to the stabilizer system in the "standby" position; and to remove the port helm potentiometer from the ship system and connect it to the stabilizer system when in the "on" position. The pulse circuit and counter are used to provide an indication of the number of times the unit is activated and measure the total "on" time for the system. The counter and timer circuits are not necessary for proper system operation; however, the time delay device is used to switch from "system standby" to "system ready" indicating a proper warm-up period. This period is required to establish proper adaptive control constants.

Connector P5 connects the port helm potentiometer to the helm unit. The potentiometer end taps have been lifted and appear as pins D and F while the center tap is found on pin E. Pins A and C are connected to the port potentiometer end taps and pin B is center tap, as shown in Figure 2. Thus, when S_1 is in the "off" and/or "standby" position, the port helm potentiometer is electrically connected in the normal, or unmodified, manner. In the "on" position, S_1 breaks all contact between the ship's normal steering system and the port helm potentiometer while simultaneously connecting the potentiometer to the stabilizer system, thereby providing a rudder command signal to the stabilizing system. When in the standby position, electronic power is supplied to the stabilizer system allowing a warm-up period.

Connector P6 connects the control unit to the helm unit. Pin A brings up +15 VDC, Pin B -15 VDC, and Pin D is common from the power supply which is located in the control unit. Pin C carries the rudder control signal from the helm to the controller, and Pin E activates a coil relay. When in the "off"/"standby" positions, the coil relay is deenergized applying a zero signal to the actuator, which is discussed later. In the "on" position, the coil relay is energized and the stabilizing signal is transmitted to the actuator. This provision for zero output during all but the "on" mode is to facilitate the clutching conversion from ship system to stabilizer system, as will be further explained under the sections entitled "Controller Unit" and "Actuator Units." Pin F of connector P6 carries the 115 VAC return while Pin G is 115 VAC 60 Hz main power. Connector P7 is used to provide 115 VAC 60 Hz power from the ship system.

CONTROLLER UNIT

1. Purpose:

Process incoming signals in order to provide command signals to the actuators which will result in rudder motions which will provide roll stabilization as well as desired course changes.

2. Location:

Near overhead at centerline on transom in after steering compartment.

3. Principle of Operation:

The controller processes incoming signals and provides an "error signal" to the actuator which causes the rudder to move so as to minimize the error signal. That is, the controller directs the actuator to move the rudder according to a command signal. This command signal is composed of the helm signal and an oscillatory stabilizing signal. The helm signal generally provides for course changes while the stabilizing signal provides roll stabilization with a negligible effect on course or speed. It is seen in Figure 3 that the actual rudder command is given by:

$$\delta = H_c + K_2\dot{\phi} \tag{1}$$

where δ = rudder angle

H_c = helm command

$K_2\dot{\phi}$ = stabilizing signal (see Appendix A)

$\dot{\phi}$ = roll rate signal

K_2 = control constant

In practice, the rudder oscillates about the helm command (H_c) at a rate dependent on $\dot{\phi}$ and at an average excursion of slightly over 5 degrees. The actual rudder excursions will, of course, often exceed 5 degrees. The ability of the controller to maintain an almost constant stabilizing rudder angle excursion ($K_2\dot{\phi}$) under widely varying values of $\dot{\phi}$ is due to an adaptive capability in the selection and generation of the K_2 value. A brief discussion of the need for this adaptability and the method of implementation is given in Appendix A. The controller is therefore seen to consist of two primary circuits: the adaptive circuit which generates the $K_2\dot{\phi}$ value and the processor circuit which processes incoming signals in order to satisfy Equation (1). These circuits are now discussed separately in the following section.

4. Schematic Description:

a. Adaptive Circuit: The adaptive circuit is contained primarily on cards 3, 4, and 5 located as shown in Figure 4. The schematic for the controller is given in Figure 2. The roll rate signal ($\dot{\phi}$) provided by the roll rate sensor is initially filtered by

a 10 Hz filter to reduce signal noise. Amplifier 1-A with unit gain may be bypassed via switch S_3 which will cause the RRS system to destabilize the vessel in roll. That is, S_3 will shift the rudder motion by 180 degrees and the system will force roll the ship. This switch is provided mainly for test purposes and was installed after the photographs in Figure 4 were taken. S_3 is mounted on the forward edge of card 5. Amplifier 1 provides conditioning for the filtered roll rate signal and is set for a circuit gain of 10.4:1. Amplifiers 2 and 3 form an absolute value (full wave rectifying) circuit producing a nonnegative output at all times. Amplifiers 4 and 6, in combination with integrator 5, act as a smoothing filter whose output is compared to a preset null voltage of +1 volt DC provided by the potentiometer and diode input to amplifier 7. This arrangement ensures that the divide circuit will always see a -1 volt or more negative signal at input X_{in}. The divide circuit outputs a signal which is inversely proportional to the X_{in} input; thus, the larger the roll rate signal, the smaller the divide output. This output is then further smoothed by amplifiers 8 and 10 along with integrator 9 which act as a second smoothing filter. The X_{in} input of the multiplier is then equivalent to the desired K_2 value. The filtered and conditioned roll rate signal is applied to the Y_{in} input, yielding an output equal to $K_2\dot{\phi}$ which is further conditioned by amplifier 11 before being applied to the controller circuit (as an addition to the helm signal) at the input to A19. Table 1 gives representative values at the various points within the adaptive control circuit and may be used in conjunction with the "Controller Alignment Procedures" section contained later in this document.

b. Processor Circuit: The processor circuit accepts the helm signal (see helm unit description) as input to A18 which conditions the signal to 6V = 30° rudder. The stabilizing signal from the adaptive circuit is combined with the helm signal and both are conditioned by A19 so that 1° of rudder produces 0.200 VDC. The back to back diodes with 100K potentiometers are used to limit the output voltage to approximately $\pm$6.6 VDC which, in turn, limits rudder travel to approximately $\pm$33°, thereby preventing the probability

of hitting the rudder stops during large helm commands. This rudder command signal (see Figure 3) is now compared with the actual rudder position. The rudder position sensor signal is conditioned by A20 to 1° of rudder angle = 0.200 VDC so that it is identical to the calibration of the rudder command signal. At this point we have developed an error signal which represents the difference between the desired rudder position and the actual rudder position.

The circuit now branches into two halves, one side to provide control to the port steering pump and the other side to provide control to the starboard steering pump. Only one side will be discussed due to their similarity. A21 is used to increase the error signal gain such that 1° of rudder = 2.0 VDC. The back to back Zener diodes limit the maximum output of A21 to approximately ±3.4 VDC to prevent the existence of saturation in the next stage. The paired transistors with potentiometers are used to fine adjust the positive and negative voltage output limits of A21. The error signal is now compared with the pump stroke lever arm position coming from A23. It is the position of this lever arm which controls the director of rudder travel (forward for left rudder, aft for right rudder) and also the rate of rudder movement (further forward or aft for increasing rate). The actual setup of A21, A23, and the limiting circuits is discussed in the section on "Controller Alignment Procedures." A22 is used as a summing amplifier for the error signal and pump stroke lever position signal. The resulting signal is such that the pump stroke lever will be positioned to move the rudder in the proper direction at the desired rate to reduce the error signal to zero. A24 and the power transistors produce the required current to operate the MOOG valve which physically positions the pump stroke lever through a series of linkages, as discussed in the following section.

ACTUATOR UNITS

1. Purpose:

The two actuator units position the pump stroke lever arms on the steering pumps according to a command from the controller unit and

provide a clutching capability which allows efficient shifting between the stabilization and normal steering modes.

2. Location:

One actuator sits atop each of the two steering pumps located in after steering.

3. Principle of Operation:

Hydraulic fluid from the ship steering system is utilized in the RRS system to develop the mechanical counterpart to the electrical signal produced in the RRS controller. Initially, the hydraulic fluid is ducted through quarter inch stainless steel tubing to two independent manifolds. Flow through the aftmost manifold is controlled by a Parker-Hannifin hydraulic valve before reaching a linear hydraulic actuator. Flow through the forwardmost manifold is controlled by a MOOG valve before reaching the ROTAC rotary hydraulic actuator. Both valves independently control the return flows of hydraulic fluid to the steering system reservoir. The controlling signals for both valves are received through electrical cables from the controller. It should be noted that the Parker-Hannifin is a two-port valve, thus the linear hydraulic actuator (hydraulic cylinder) will be either fully extended or fully retracted, thus activating the clutch mechanism. Because the MOOG valve is a four-port valve, regulation of the rotary actuator occurs such that a rotational position can be held at any point or rotational movement may occur in either direction. The flow circuit with manifolds, valves, and actuators can be visualized in the exploded isometric view, Figure 5.

The transition from normal steering mode to stabilization mode is facilitated via the use of a sliding clutch mechanism. The position of a sliding cylinder-yoke assembly is controlled by the linear hydraulic actuator (hydraulic cylinder). When the actuator shaft is fully extended the normal steering mode is engaged, and when fully retracted the stabilization mode is engaged. The rotational position of the sliding cylinder directly controls the pump stroke lever. When the free end of the pump stroke lever is vertical, the pump stroke rate is zero, and the position of the rudder is maintained. The corresponding sliding cylinder position is horizontal. In the normal steering mode (i.e., stabilization disengaged), the hydraulic cylinder shaft is fully extended and the

sliding cylinder inserted in the port clutch jaw. A direct linkage from the differential output to the pump stroke rate is now achieved and the helm is in full control.

When the stabilization system is engaged, the hydraulic cylinder will retract its shaft, positioning the sliding cylinder inside the starboard clutch jaw. The position of the pump stroke lever will be directly coupled to the rotary actuator shaft, so that any rotational movement of the hydraulic actuator will be causal to the pump stroke rate. In practice, the signal from the controller orders the MOOG valve to rotate the hydraulic actuator shaft, thus determining the pump stroke rate. A feedback pot behind the hydraulic actuator senses the rotation and informs the controller when the desired pump stroke rate has been obtained. Consequently, once stabilization has been engaged, continuous signals from the controller and to the actuator, and vice versa, produce constant changes in the pump stroke rate. Thus, rudder position is maneuvered to counteract ship roll.

CONTROLLER ALIGNMENT PROCEDURES

The following alignment and calibration procedures require electronic test equipment normally available only in an electronics laboratory. It is strongly recommended that these procedures not be attempted without the equipment comparable to that listed in Table 2. Throughout this section all voltages are referenced to the power supply common and all voltage measurement tolerances are ±0.010 volts unless otherwise stated. This section is divided between the adaptive circuit and the processor circuit, as was the schematic description within the "Controller Unit" section.

Adaptive Circuit: The alignment procedure consists of two parts: the first using DC input signals and the second using AC input signals. It is recommended that unless the unit has been abused, the DC signal procedures be skipped and that one proceed directly to the AC signal alignment procedures. It if becomes evident that a more thorough approach is required, one may then return to the DC signal procedures.

First, the DC input signals. Refer to Figure 4 for card and potentiometer locations and to Figures 2, 6, and 7 for schematics of the

controller, card 3 and card 5, respectively, which contain the components referred to in the first seven steps. Supply 115 VAC 60 Hz power to the controller via Pins B and C in connector P1 to provide ±15 VDC power to the controller circuits.

1. Throw switch S4 to the right (toward board center) and shunt TP-20 to TP-21. This provides a zero input to the adaptive circuit entering at amplifier 1A. Ensure that TP-19 is at zero using the trim pot (R3) located just in front of switch S4. (Use of extender board as listed in Table 2 is helpful.)
2. Adjust R8 for zero output at test point (TP) 1.
3. Adjust R13 for zero output at Junction of D2, R12, and R14.
4. Adjust R17 for zero output at TP2.
5. Using R25 for course adjustment and R21 for fine adjustment, set TP3 at zero volts.

   Note: Due to the nature of the adaptive circuit, the two smoothing filters have long time constants. Therefore, allow the circuit to stabilize before making further changes. Stabilization requires approximately 4 minutes.
6. Adjust R30 for the lowest possible voltage at TP4 and then adjust R31 for zero volts at TP4.
7. Adjust R30 for -1.000 VDC at TP4.

Steps 8 through 11 refer to card 4 whose schematic is given in Figure 8.

8. Referring to Appendix B, locate Z_{in} on the divider (AD533) and adjust R32 to bring Z_{in} to +1.000 ±0.005 VDC.
9. Adjust R43 for zero voltage on the center tap.
10. Using R51 for course adjustment and R47 for fine adjustment, set TP6 at zero volts.

    Note: Allow circuit to stabilize between adjustments.
11. Referring to Appendix B, locate Z_{in} on the multiplier (AD533) and check to determine that Z_{in} is at zero volts. If Z_{in} is not within tolerance (±0.010 VDC), use the adjustment procedures in Appendix C to adjust R52 through R56.

    Note: These adjustments require that the X_{in} and Y_{in} terminals be open. Additionally, step 5, as given in Appendix B, should be disregarded.

12. Adjust R59 for zero voltage at TP7.

Steps 13 through 16 refer primarily to card 3, Figure 6.

13. Remove the shunt from TP-20 and TP-21 on card 5. Using TP-20 as input and TP-21 as common, apply +0.100 ±0.005 VDC to the circuit.
14. Adjust R10 for -1.040 VDC at TP1.
15. Adjust R15 for +1.040 VDC at TP2.
16. TP3 should indicate +1.040 ±0.020 VDC. If TP3 is not in this range, check components R18 through amplifier 6 for out of specification characteristics.

    Note: Some adjustment of TP3 voltage may be made by sliding the voltage of TP2 within its allowable range using R15.
17. Adjust R26 for -3.536 ±0.020 VDC at TP4.
18. TP5 should yield 2.828 ±0.020 VDC; however, the actual value is not as important as its linearity with the reciprocal of X_{in}. That is,

$$V_0 = K(10/X_{in}) \qquad K \sim 1.0$$

    should be satisfied within 5 percent for $-1.0 \leq X_{in} \leq 10.0$ VDC. If tests of the divider circuit indicate otherwise, the alignment procedures given in Appendix B should be followed.

    Note: These adjustments require the X_{in} and Y_{in} terminals be open.
19. Adjust R43 until TP6 equals 1.32 times the voltage at TP5.

    Note: Allow time for the circuit to stabilize between adjustments.
20. The multiplier output at this time should be one-tenth X_{in} times Y_{in}, or approximately 70 percent of the voltage at TP5.

    Note: This is true only for an input of +0.100 VDC at Pin 2 of the card 5 cinch connector.

We now continue with the AC signal alignment procedures. As with the DC signals, the AC signals are applied to TP-20 as input and TP-21 as common on card 5. Refer to Figures 2, 4, 6, 7, 8, and to Table 1.

1. Apply a ±0.150 VAC at a period of 10.8 seconds (frequency = 0.0926 Hz) to the circuit via TP-20 and TP-21. (See step 13 of controller alignment procedures.)

2. As shown in Table 1, TP1 should yield an AC signal of ±1.560 ±0.050 VAC. R10 may be used to adjust this output.
3. TP2 should indicate a rectified wave form having positive polarity and peaks of +1.560 ±0.050 VAC. Do not adjust this voltage at this time.
4. TP3 should indicate a positive voltage of +0.976 V peak. If TP3 is not within ±0.050 V, adjust R10 until it is. If successive peaks indicate voltages which differ by more than 0.050 V, refer to steps 1 through 4 of the DC signal procedures to adjust the offset voltages of amplifiers 1, 2 and 3. Further adjustment of TP3 voltage may be made using R21 and R25. Refer to steps 1 and 5 of the DC signal procedures.

   Note: Allow time for circuit to stabilize between adjustments, i.e., 5 minutes.
5. TP4 should indicate a voltage of -3.320 ±0.050 V. Table 1 indicates that in the circuit tested amplifier 7 had a gain of approximately 3.4:1. If the successive peaks at TP4 differ by more than 0.050 V, refer to the adjustment for R30 and R31; steps 1, 6, and 7 in DC signal procedures. If the magnitude of TP 4 voltage is too high or low, refer to steps 13 and 17, also under the DC signal procedures.
6. See Appendix B for alignment of AD-533 divide circuit. The divide circuit output at TP5 should be -3.012 ±0.100 V. Ideally this TP5 voltage is 10 times the reciprocal of the voltage at TP4. Again, as stated earlier, the actual value is not as critical as the linearity over a range of values at TP4 of -1.000 V to -10.000 V.
7. TP6 should indicate a voltage of 3.976 VDC or 1.32 times TP5, see step 19 of the DC signal procedure. Since the original sinusoidal signal has been rectified and is now smoothed for the second time, TP6 should exhibit an almost DC voltage.
8. TP7 should indicate a sinusoidal voltage of 1.150 ±0.050 VAC. If successive peaks are not within 0.075 V of each other, refer to steps 1 and 12 of the DC signal procedures. The amplitude of TP7 may be adjusted using R58.

9. Repeat steps 1 through 8 above for sinusoidal voltages with amplitudes of ± 0.060 VAC and ± 0.500 VAC and compare with values obtained for the ± 0.150 VAC test case. Variances between TP7 voltages should not exceed $\pm 1.15 \pm 0.10$ VAC for any test case. Larger variances than allowed generally indicate a nonlinearity in the divider circuit as noted in step 18 of the DC signal procedures, see also step 6 above.

Processor Circuit: Preinstallation alignment of the processor circuit is achieved with DC signals only. In several places the circuit values depend on electrical or physical characteristics of the ship steering system. In these instances, the circuit variables will be set such that final alignment will necessitate relatively small additional adjustments. Final alignment procedures are discussed in the "Controller Installation" section.

DC signals are applied to the processor circuit via Pin F (signal) and Pin E (common) of connector P1 as located in Figures 2 and 4. Card 4 should be removed from its connector to prevent the adaptive circuit signal from entering the processor circuit via R71 and amplifier 19. Supply 115 VAC 60 Hz power via Pins B and C in connector P1 to provide ± 15 VDC power to the controller circuits. Refer to Figures 2, 9 and 10 for the following steps.

1. Shunt Pins E and F on connector P1 which provides zero input to amplifier 18 via R64. Shunt Pins D and E of connector P1 to close relay contacts 3 and 4, and 7 and 8, located at the outputs of amplifiers 21P and 21S, respectively. These switch contacts are normally controlled via the helm unit, as discussed in the "Actuator" section.

   Note: During the initial zeroing process it is recommended that tolerances be kept as small as possible.
2. Adjust R82 for zero volts at TP-13.
3. Adjust R68 for zero volts at TP-8.
4. Adjust R130 for zero volts at TP-9.
5. Adjust R94 for zero volts at TP-10.
6. Adjust R116 for zero volts at TP-16.
7. Adjust R131 for zero volts at TP-14.

8. Adjust R132 for zero volts at TP-17.
9. Adjust R133 for zero volts at TP-11.
10. Adjust R134 for zero volts at TP-12.
11. Check all test points located on Cards 1 and 2. Any large non-zero voltages indicate circuit abnormalities and should be resolved using Figure 2 before proceeding.

    Note: Amplifiers 21P and 21S will be set for gains of 10:1, while amplifiers 22P and 22S will be set for gains of 2:1. Offset voltages following these amplifiers may therefore be significant if input voltages are not very nearly zero.
12. Remove the shunt from connector P1 Pins F and E. Using Pin F as signal input and Pin E as common input +1.500 VDC with the voltage source. This voltage will be termed the source voltage.
13. Adjust R69 for -7.500 VDC at TP-8.
14. Adjust R72 for +7.500 VDC at TP-9.

    Note: Card 4 should be removed from its connector as stated earlier. Potentiometers R73 and R74 should be adjusted such that their wipers are at the supply voltage (±15 VDC) end of their windings, thereby eliminating their limiting effects.
15. Adjust R73 until TP-9 is reduced from +7.500 VDC down to +6.0 VDC.
16. Reverse the source voltage thereby inputting -1.500 VDC to amplifier 18.
17. Adjust R74 until TP-9 is reduced from -7.500 VDC down to -6.0 VDC. Steps 9, 10 and 11 result in limiting the rudder travel to ±33 degrees when the unit is installed.
18. Reduce the source voltage from -1.500 VDC down to -0.035 VDC. This should result in a TP-9 voltage of approximately -0.175 VDC. The source voltage may be varied to obtain a TP-9 voltage of -0.175 ±0.020 VDC. Ensure that TP-13 is at zero volts, otherwise adjust it to zero using R82.
19. Adjust potentiometers R87, R88, R109 and R110 such that their wipers are at a common end of their windings thereby eliminating their limiting effects.

20. Adjust R86 until TP-11 is 10.0 times the negative of TP-9, that is, set amplifier 21P for a gain of 10.0:1.
21. Using R108 similarly adjust the gain of amplifier 21S for a gain of 10.0:1.
22. Ensure that TP-10 and TP-16 are at zero volts, otherwise adjust them to zero using R94 and R116, respectively.
23. Adjust R100 until TP-12 is twice the negative of TP-11, that is, set amplifier 22P for a gain of 2.0:1.
24. Adjust R122 until TP-17 is twice the negative of TP-14, that is, set amplifier 22S for a gain of 2.0:1.
25. Adjust R102 until TP-15 is -0.6625 times TP-12, that is, set amplifier 24P for a gain of -0.6625:1.
26. Adjust R124 until the voltage at TP-18 is -0.6625 times TP-17, that is, set amplifier 24S for a gain of -0.6625:1.

    Note: If TP-9 is indeed at -0.180 VDC, then TP-15 and TP-18 should both be at +2.380 VDC.
27. Increase the source voltage to -0.060 VDC. This should result in a +3.00 VDC signal at TP-11 and TP-14, assuming that the transistor limit circuits are not clipping the signal.
28. Adjust R87 until TP-11 is at +2.0 volts.
29. Adjust R109 until TP-14 is at +2.0 volts.
30. Reverse the polarity of the source voltage.
31. Adjust R88 until TP-11 is at -2.00 volts.
32. Adjust R110 until TP-14 is at -2.00 volts.

Preliminary adjustment of the following three feedback amplifiers will complete the preinstallation alignment of the processor circuit.

33. Remove the source voltage signal from Pin F of connector P1, increase the voltage to -2.000 VDC. Do not remove the source voltage common from Pin E of connector P1.
34. Ground Pin A of connector P4. Ensure that TP-13 is at zero voltage using R82 to trim if necessary. Remove the ground and apply the source voltage signal to Pin A of connector P4 and adjust R83 until TP-13 is at +3.600 VDC. This sets the rudder angle feedback amplifier (#20) at a gain of 1.8:1. Remove the source voltage signal from Pin A, P4.

35. Ground Pin C of connector P2 and ensure that TP-16 is at zero voltage using R116 to trim if necessary. Apply the source voltage signal to Pin C of connector P2 and adjust R119 until TP-16 is at +6.000 VDC. This sets the starboard pump stroke lever position feedback amplifier (#23S) at a gaon of 3.0:1.
36. Ground Pin C of connector P3 and ensure that TP-10 is at zero voltage using R94 to trim if necessary. Apply the source voltage signal to Pin C of connector P3 and adjust R97 until TP-10 is at +6.000 VDC. This sets the port pump stroke lever position feedback amplifier (#23P) at a gain of 3.0:1. Throw switch S4 back to the left which will return the filtered rate sensor signal to the input of amplifier 1A. Remove all shunts and test equipment and reconnect all connectors.

This completes the alignment of the processor circuit.

INSTALLATION PROCEDURES

It is most important that the ship steering system be operationally correct prior to this installation. Of primary importance is the equalization of the port to starboard and vice versa rudder rate which is dependent to some extent on physical adjustments.

PHYSICAL INSTALLATION

The mounting of the various components is not generally critical, except as will be explained, as each component is fitted and then calibrated or adjusted to provide for proper functioning. This section will describe the mounting procedures used on the JARVIS and MELLON installations. Specific details will be given only as required for proper functioning of the various components.

The helm unit may be mounted in any convenient location on the bridge. The MELLON installation has the helm unit located in the front plate of the bridge console while on JARVIS it is located in the overhead panel near the ship's horn lever. It is wise to select the location prior to installing the fore to aft cable so that its forward termination is at the helm unit location.

The controller unit may be mounted in any location convenient to the actuators and rudder angle feedback potentiometer. This unit contains the roll rate sensor and must be aligned so that this sensor is indeed oriented with its rate axis aligned with (parallel to) the roll axis of the vessel. While the two axes do not have to be co-incident, the installation should be made such that they are not only parallel but displaced as little as is convenient. This unit, like the helm unit, is self-contained requiring only four cable connections. Both MELLON and JARVIS have the controller mounted on a fabricated bracket near the centerline just forward of the transom in after steering. The controller unit should be reasonably isolated from shock, vibration, and heat.

The port and starboard actuators mount piggyback on the port and starboard pump stroke swash plate cylinder housings located atop the steering pumps. Installation is accomplished by the removal of the eight bolts, four on each side, of each of the cylinders. These original bolts must be replaced with longer ones to accommodate the additional thickness of the actuator side plates. The new pump stroke rate lever replaces the original, as does the new linkage rod. Installation of the remaining clutch linkage is straightforward. THE LENGTH OF THE SHIP LINKAGE ROD TO CLUTCH JAW (#20, TABLE 3) MUST BE ADJUSTED TO PROVIDE ZERO POSITION OF THE SWASH PLATE WHEN HELM COMMAND AND ACTUAL RUDDER ANGLE ARE THE SAME. This adjustment will be discussed in the section to follow, entitled Final Calibration and Adjustment.

The hydraulic filter, fluid lines, and shutoff valve supply and control the hydraulic fluid to the actuator. The fluid supply is obtained by tapping the supply to the port SPERRY MARINE rotary actuator between the "R" valve and the 25y filter. This fluid line is one-half inch of stainless tubing, our installation broke this line and inserted a one-half inch tee fitting. The tee branch leading to a shutoff valve while the straight replaced the original line. This shutoff valve allows fluid flow to be shut off should the actuators require maintenance while underway. The shutoff valve leads to a ten micron, 50 GPM filter and then to another tee. At this point the line splits with one end going to each of the actuators. In order to ease the installation, one-fourth inch tubing was used between this second tee and the actuator

inlets. The drain line from each of the actuators should return to the port reservoir tank as that is where the fluid originated.

The linear rudder angle feedback potentiometer body was mounted on the aft side of the port ram cylinder, parallel to the ram itself to prevent binding during travel. The free rod end was mounted to the ram crosshead thus indicating linear ram travel which closely approximates rudder angle. The position of the potentiometer slider should be near its central position when mounted with the rudders at amidship.

FINAL CALIBRATION AND ADJUSTMENT

The helm potentiometer, which is the port or starboard ship's helm potentiometer, as discussed earlier, should be positioned to its zero (amidship) position. Hook up all cables. Turn the unit to "on." Amplifier 18 (Figure 9) should then be adjusted using R68 to provide zero output at TP-8. Remove card 4 from the controller. This removes the signal from the adaptive circuit to amplifier 19 leaving only the helm signal. Adjust R130 to provide zero output at TP-9. Leave card 4 out for the following calibrations.

It is necessary to adjust amplifier 18 to provide 0.200 volts per degree of desired rudder as commanded by the helmsman. This is easily done by positioning the helm potentiometer to 20 degrees left rudder and adjusting R69 to provide 4.00 volts at TP-8, that is, 0.200 times 20 = 4.00. This voltage should be negative, if it is not, reverse the wires on Pins A and B of connector P6. This reversal can be most easily made at the terminal strip between the RRS helm selector switch and connector P6.

Once R69 has been adjusted, move the helm potentiometer to 10, 20 and 30 degrees right and left and note the voltages. This should be +2.0. +4.0, +6.0, -2.0, -4.0, and -6.0 volts. In most cases, the inherent inaccuracy in positioning coupled with a worn helm potentiometer will yield less than ideal results.

It is most practical to adjust R69 to provide a "best fit" value; that is, a value which remains close to the desired value throughout the range. Since amplifier 19 has unity gain, the 0.200 V per degree will be changed only in polarity at TP-9. This completes the final calibration of the helm potentiometer, and amplifiers 18 and 19.

Next, calibrate the rudder feedback potentiometer through amplifier 20. Turn the RRS system to "stand by" and using the trick wheel, position the rudder to amidships using the scale above the ram. Secure the steering pumps. Manually position the linear feedback potentiometer to obtain the smallest possible voltage at TP-13 after making sure that the voltage from R-82 is zero. If zero cannot be obtained at TP-13 by manual positioning, secure the linear feedback potentiometer at the position giving the lowest voltage and adjust R-82 until TP-13 is at zero volts. Note: The final position of the linear feedback potentiometer should be such that full rudder right and/or left does not bottom the slider. Again using the trick wheel, move the rudder to 20 degrees right and adjust R-83 until TP-13 is at +4.00 volts giving the desired 0.200 volts per degree. If the voltage is negative, reverse the leads to Pins A and B on connector P10, that is, at the feedback potentiometer. Now move the rudder 10, 20, 30 degrees right and left; TP-13 should indicate values of +2, +4, +6, -2, -4, -6 volts, respectively. This completes the calibration of amplifier 20 and the positioning of the linear feedback potentiometer.

The "Ordered Rudder Indicator" display is calibrated in a similar manner. Referring to Figure 2, adjust R605 until the ordered rudder indicator display shows zero with the helm at the zero (midship) position. The RRS unit must be in the "on" position to perform this calibration. Move the rudder to the left and right as was done in adjusting amplifier 20. Adjust R603 until the ordered rudder indicator agrees with the actual rudder position. Note that the display changes instantaneously while the rudder position does not. Allow the rudder to come to rest before each adjustment of R603. Since this display is only used when the RRS is in use, it is best to make these adjustments with both steering pumps and motors activated. With the helm calling for right rudder, make sure the right rudder indicator light is lit. If the left rudder indicator light is lit, reverse the leads to Pins 1 and 16 on the 7475 1C within the unit.

To adjust the self-centering clutches and zero the pump stroke feedback potentiometers. With the RRS unit in "stand by" we will work with the starboard side, identical procedures will apply to the port side. Ensure that R-116 is centered, i.e., not providing a signal to amplifier 23S. Turn on the starboard steering motor and allow the rudder to come

to a stop, this ensures that the swash plate control level is at its zero position. Do not move this lever until you have finished positioning the self-centering clutch. With the hydraulic valve which supplies the RRS actuators closed, position the slot on the rotac driven clutch jaw (piece #35, Table 3) until the slot is such that it will accept the sliding cylinder (piece #42, Table 3) from engagement with the port clutch jaw (piece #57, Table 3) without rotation. That is, the slots in the two clutch jaws must be parallel, this ensures that the swash plate zero position will not change when going from the ship system to the RRS system. With the starboard clutch jaw in this zero position, manually rotate the feedback potentiometer on the starboard actuator until TP-16 is at zero volts. Secure the feedback potentiometer in this position. Final zeroing may be made using R-116 if necessary. This completes the clutch zeroing for the starboard side. Adjust the port side similarly.

To make an interim adjustment on the swash plate feedback amplifiers so as to ensure that the steering system is not overstressed during the initial RRS engagement. Without engaging the steering pumps, turn the trick wheel until the commanded rudder angle is more than 10 degrees to the right of the actual rudder position. This moves the swash plate levers to a position which calls for maximum rudder rate. With the swash plate levers in this position, adjust R-119 until TP-16 indicates approximately -3.0 volts. If the polarity is incorrect, reverse the end taps on the starboard swash plate feedback potentiometer located on the starboard RRS actuator. Using R-97 make similar adjustments for TP-10, the polarities should both be negative for a commanded rudder angle which is to the right of the actual rudder angle. This completes the interim adjustments to the swash plate feedback amplifiers.

Using the trick wheel, position the rudder at amidships. Turn on only the port steering motor. With one person on the bridge and one in after steering, turn the RRS system to "on." Note: If the rudder runs away, turn off the steering motor before the rudder hits the stops. (The interim adjustment on the swash plate feedback amplifiers will assure a slow rudder rate at this time.) If the rudder runs away, reverse Pins D and E on connector P3. Using the same procedure, turn on only the starboard motor, if the rudder runs away reverse Pins D and E in connector P2.

To set a rudder excursion limit to prevent accidental crushing of the rudder stops while in the RRS mode of operation. With the RRS system on, slowly move the helm command (joy stick) until the rudder is positioned at approximately 30 degrees right rudder. Adjust R-74 until the rudder just starts back toward amidship. If the rudder will not go to 30 degrees, the limit as set in the "Controller Alignment Procedures" is already limiting the rudder excursion, adjust R74 until 30 degrees can be obtained. Move the helm command (joy stick) slowly to the right until maximum right rudder is called for. The actual rudder angle should remain at approximately 30 degrees since it is limited by R-74. With rudder command at maximum right, adjust R-74 slowly until the rudder position is 33 degrees. Repeat this process for left rudder using R-73 for the position adjustment. This completes the rudder position limit adjustment and ensures that the rudder will not exceed 33 degrees excursion with the RRS system on.

The rudder rates will now be set to 2.33 degrees per second for single pump operation. Only the starboard pump will be discussed, the port pump should be set in a similar manner. In order to perform this adjustment, it is necessary to measure the rudder rate accurately. One method is to record the voltage level at TP-13 on strip chart. Since TP-13 is calibrated at 0.200 volts per degree of rudder, the slope of this voltage trace will yield the rudder rate in degrees per second. Once the strip chart is set up, turn on the RRS system and the starboard motor. Move the helm command to maximum right and after the actual rudder angle has stabilized, turn on the strip chart recorder and move the helm command rapidly to maximum left rudder. Repeat for left to right rudder movement. Obtain the rudder rates from the strip chart using the slope of the rudder trace. The rates will be well under 2.33 degrees per second but should be nearly equal. Using R-119, decrease the gain on amplifier 23S until the faster of the rudder rates is equal to 2.33 degrees per second. That is, if initially rudder movement from left to right was faster than right to left, use R-119 to bring the left to right rate up to 2.33 degrees per second. This will require several rudder transits as one wishes to approach the desired value from below rather than exceed the rate specification. Once one direction is set, use either R-109 or R-110 to set the other direction. Use R-109 if adjusting left to right rate and R-110 if

adjusting right to left rate. Adjustment of the port motor is similar using amplifier 23P (R-97) initially and R-87 and R-88 for left to right and right to left respectively. When both pumps are set, perform a rate test using both pumps. A combined rate of 4.76 degrees per second should be obtained. This completes the rate calibration of the steering pumps.

Reinsert Card #4 to return the adaptive control input to the RRS system and turn on both motors. While the control box is open, and especially with test leads attached, the rudder will tend to hunt from side to side. With the control box loose, lift the starboard edge slowly and deliberately. The rudder should travel to the left, indicating that the roll rate sensor is functioning properly.

This completes the installation and calibration of the RRS system as installed aboard USCG cutters MELLON and JARVIS.

ACKNOWLEDGMENTS

The authors wish to acknowledge the Reverend Dr. John Ware and Mr. Richard Nigon whose efforts on the design and modeling of the adaptive control circuit contributed significantly to the success of this endeavor.

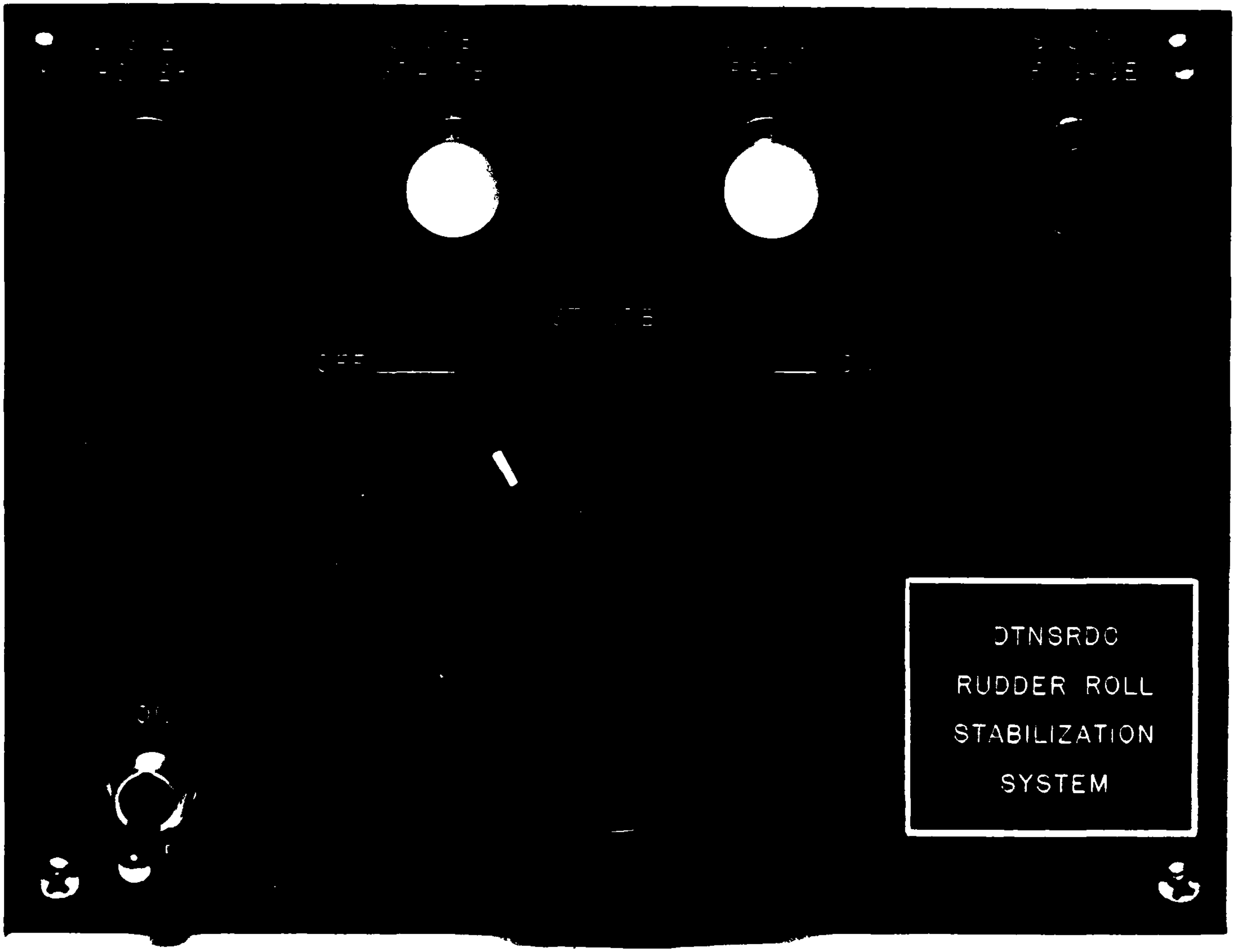

Figure 1 - Photograph of Helm Unit

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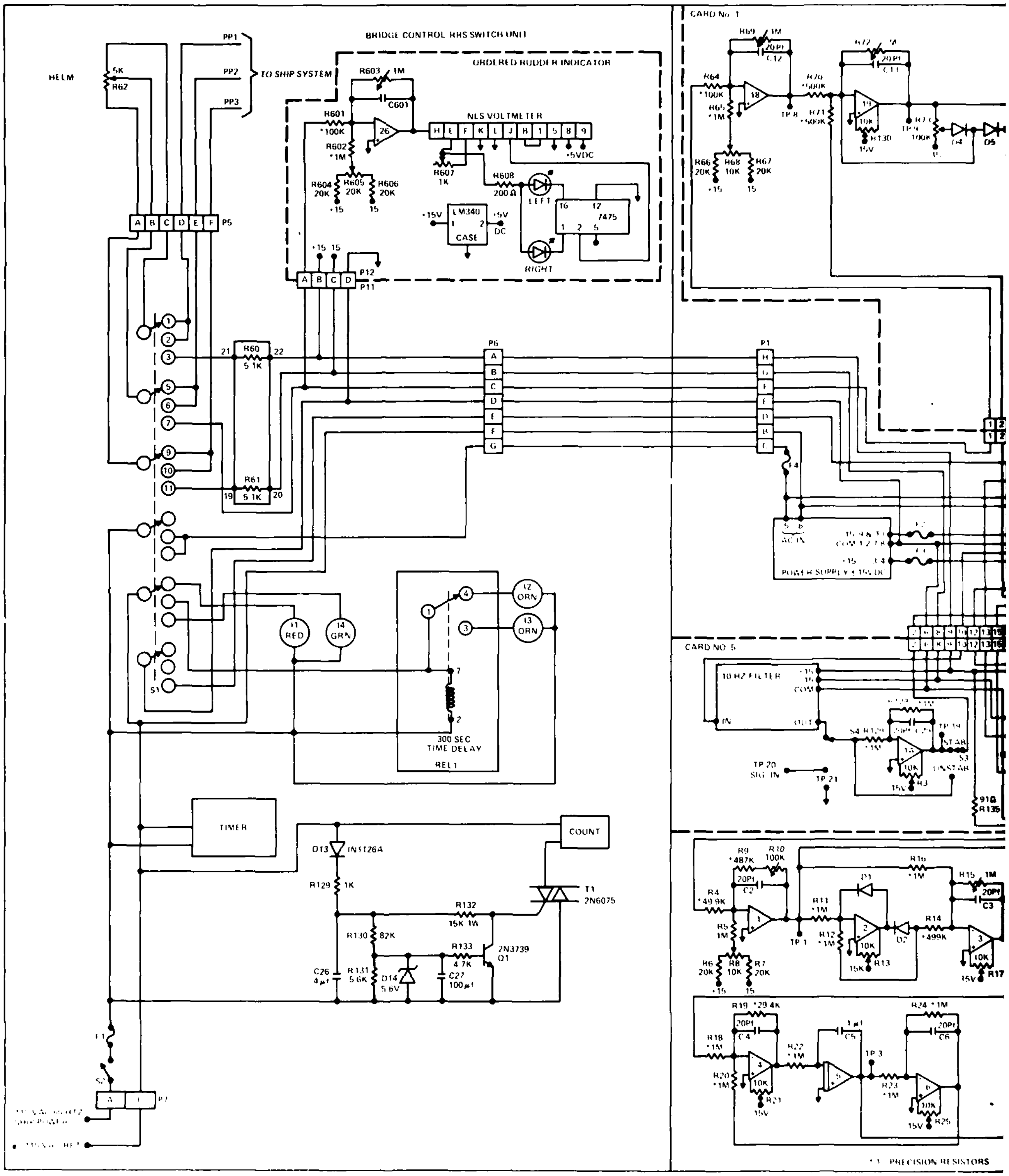

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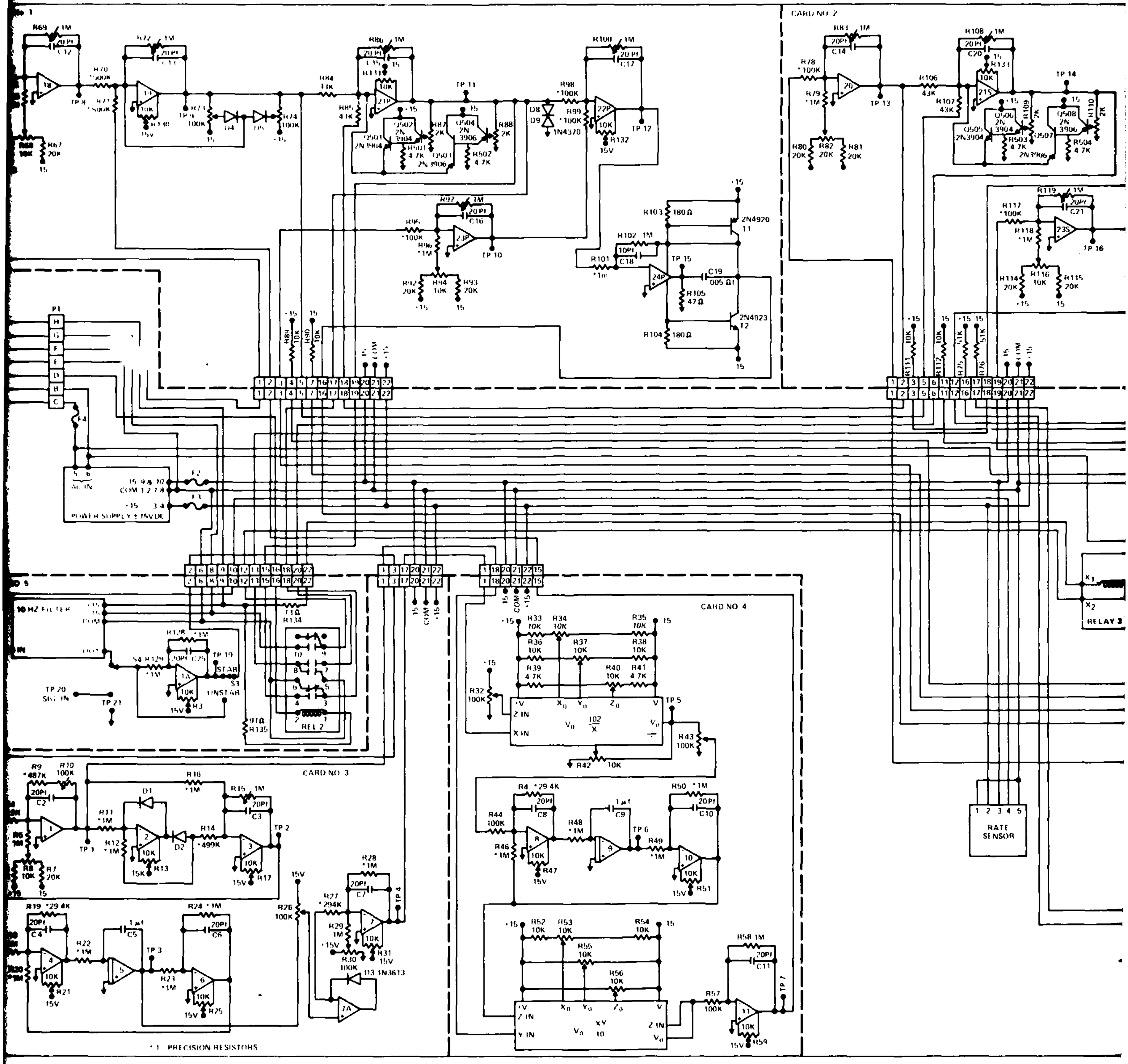
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CARD NO 3
CARD NO 4
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*1% PRECISION RESISTORS

3

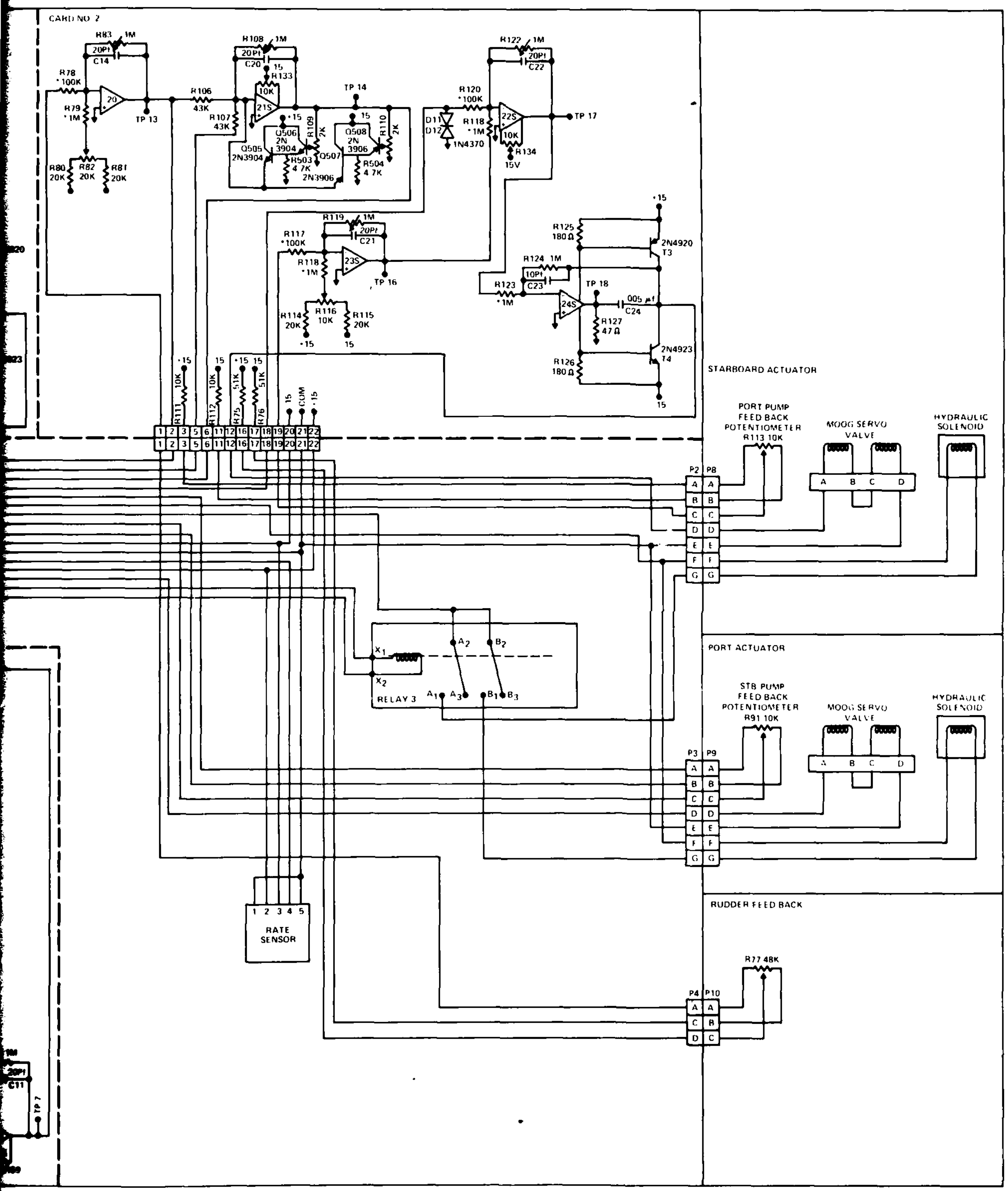

Figure 2 - System Schematic

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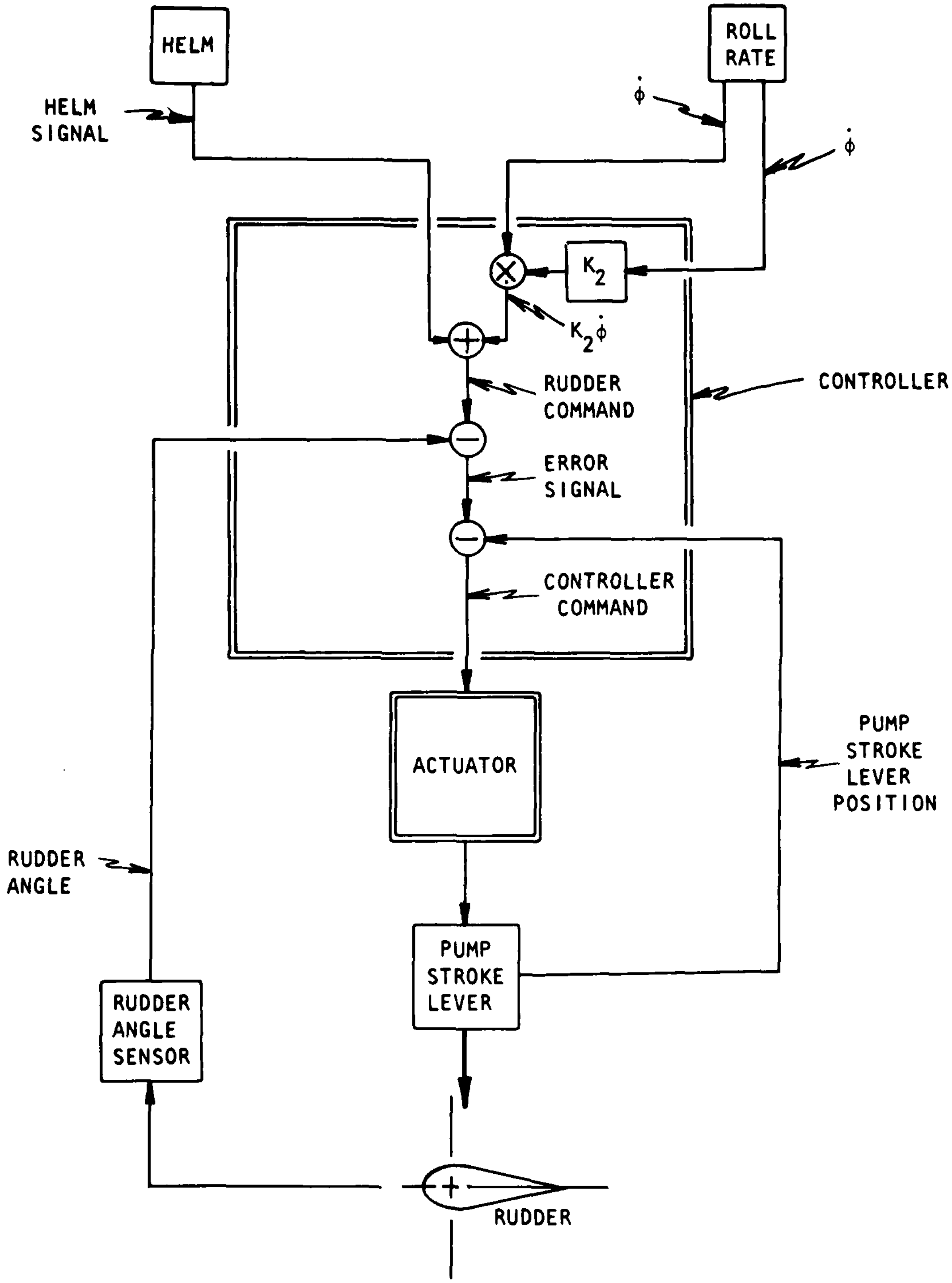

Figure 3 - Block Diagram of RRS SYSTEM

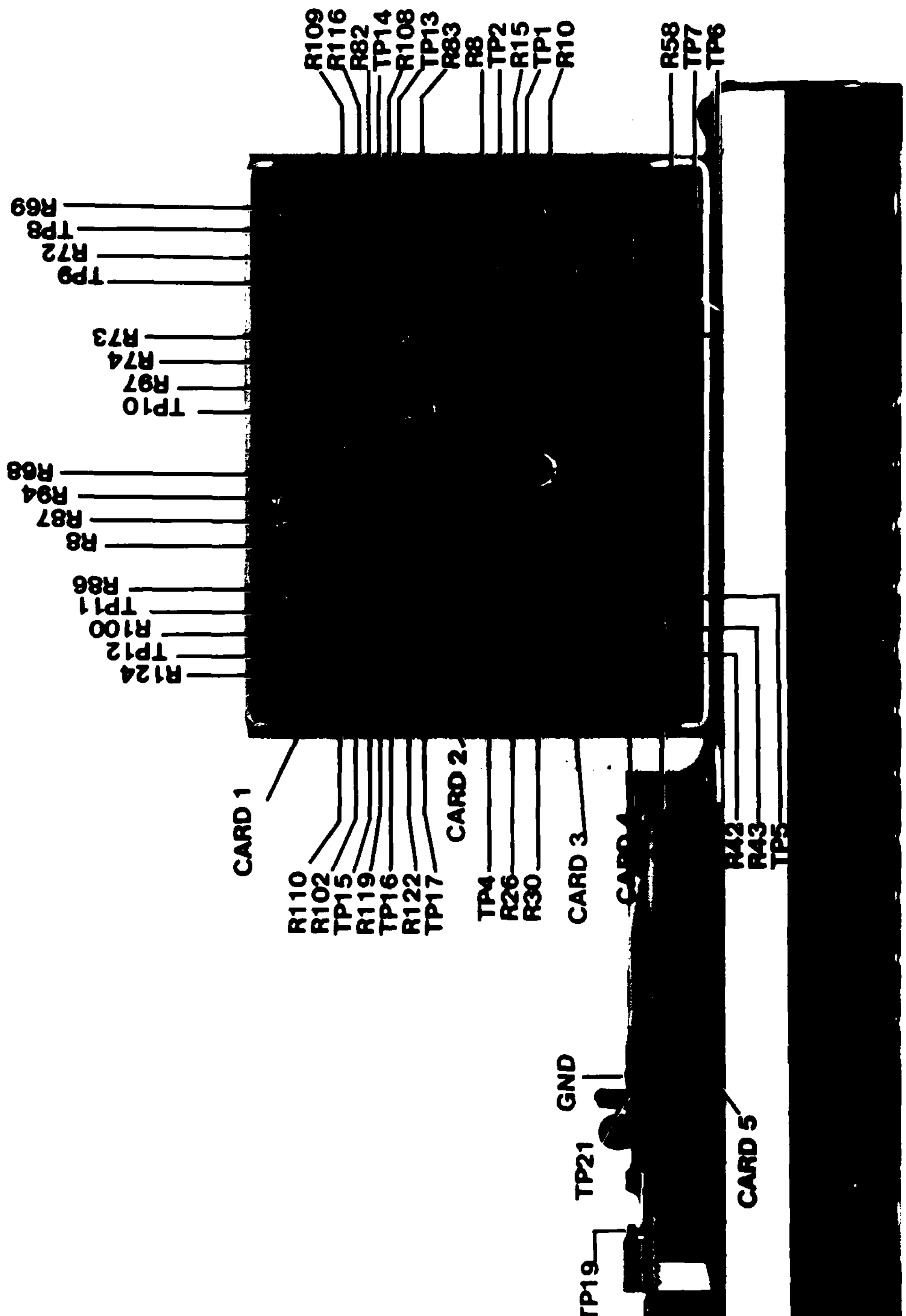

Figure 4 - Photograph of Controller

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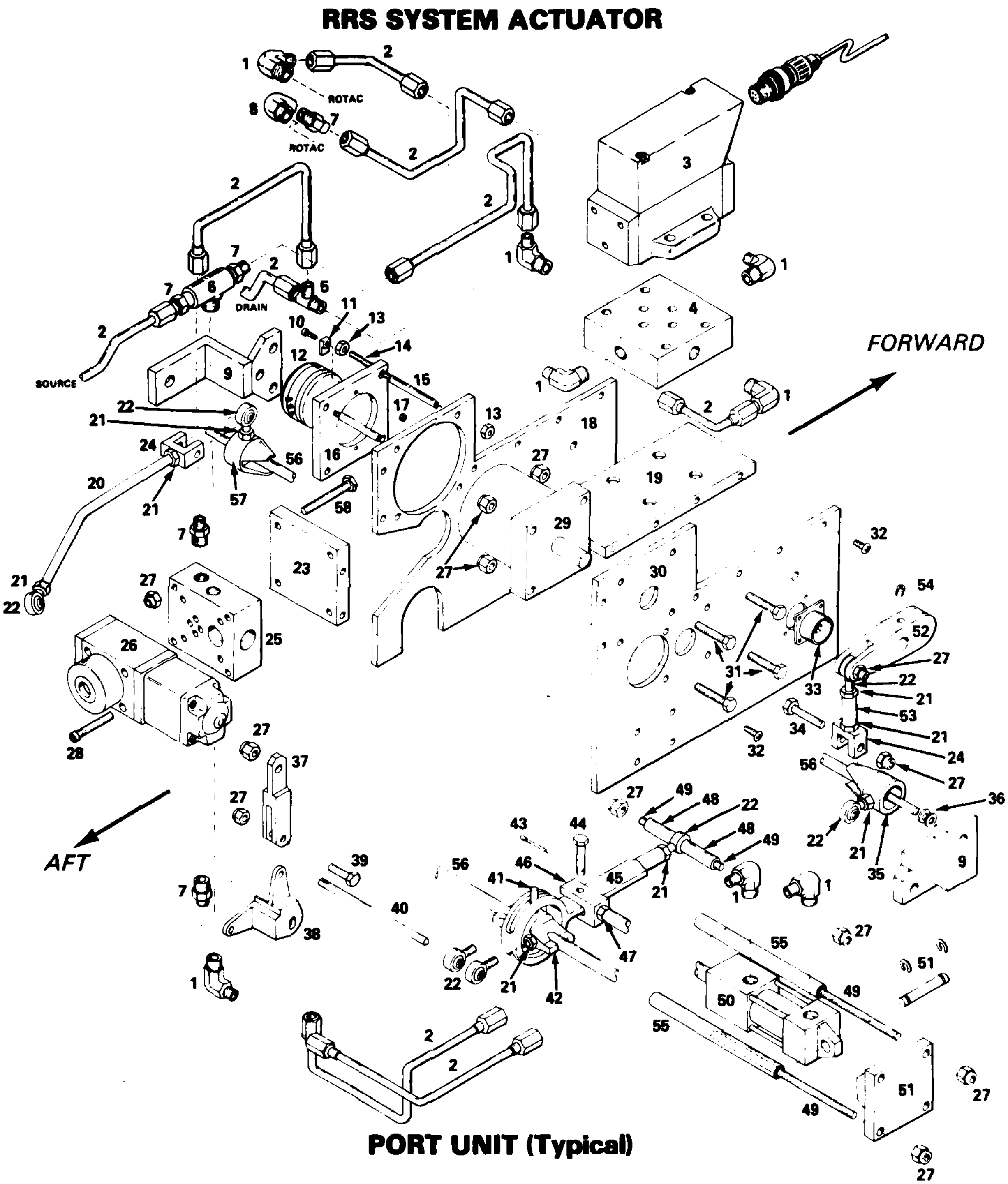

Figure 5 - Exploded View of Actuator

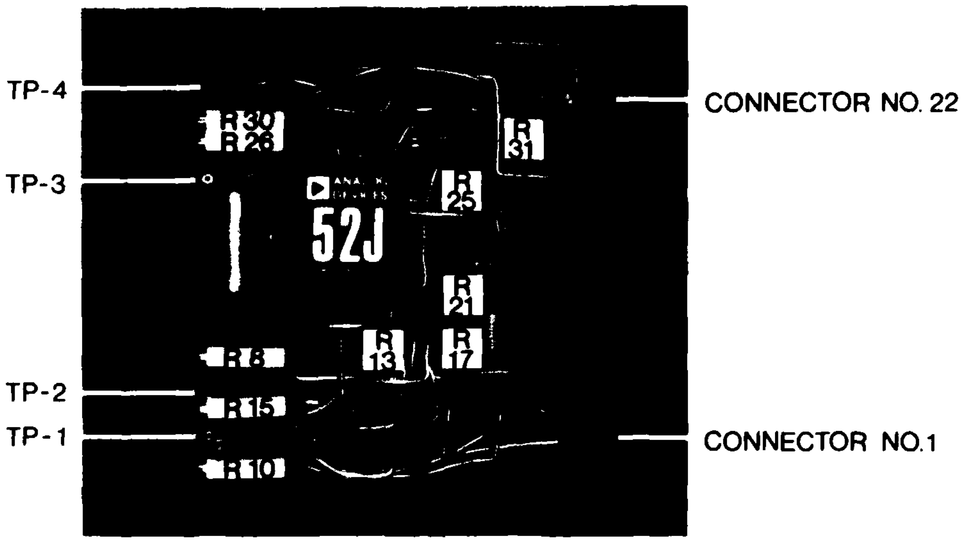

Figure 6 - Photograph of Card No. 3

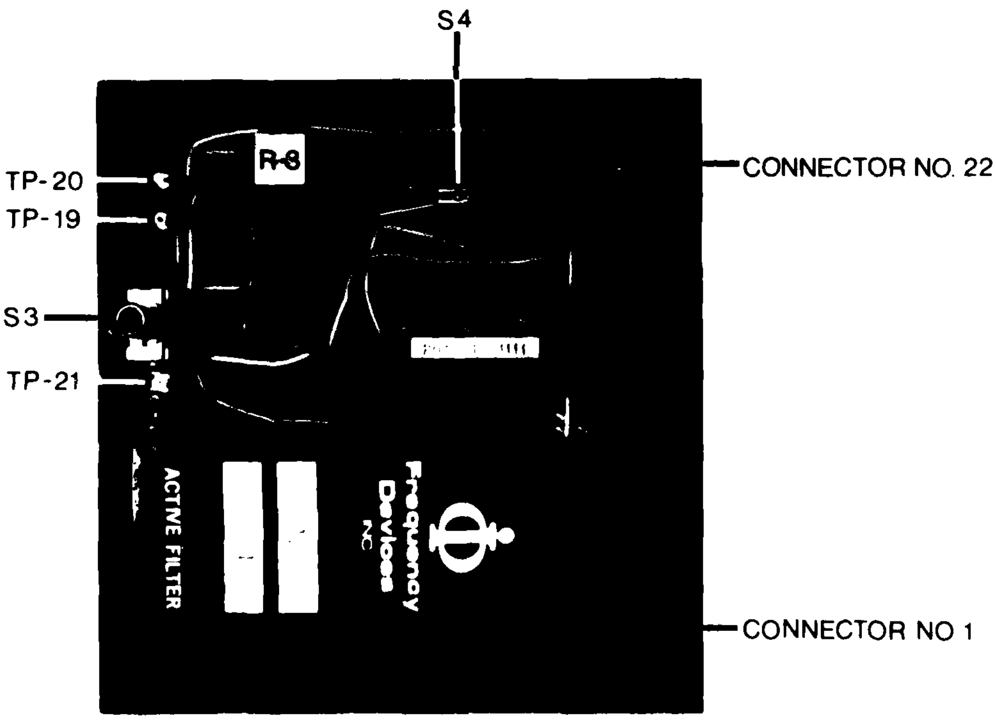

Figure 7 - Photograph of Card No. 5

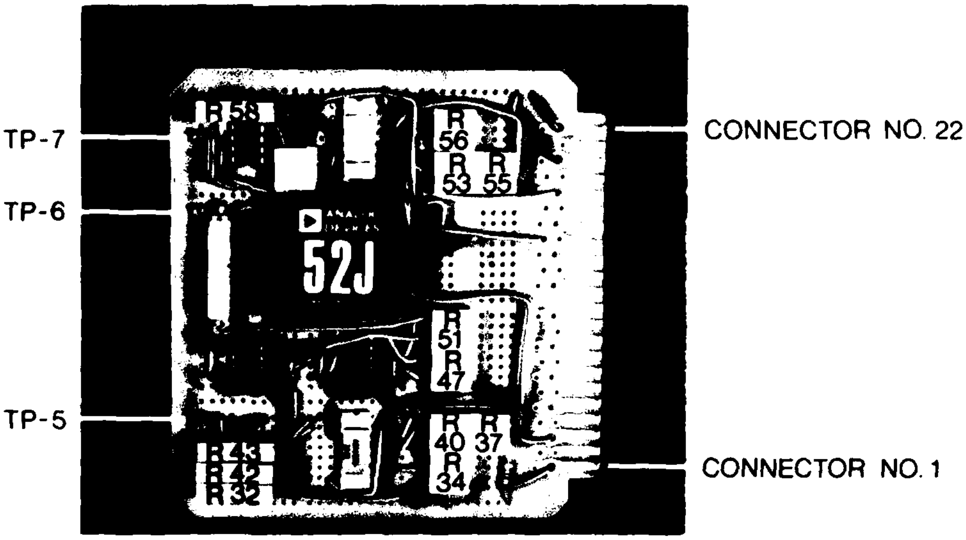

Figure 8 - Photograph of Card No. 4

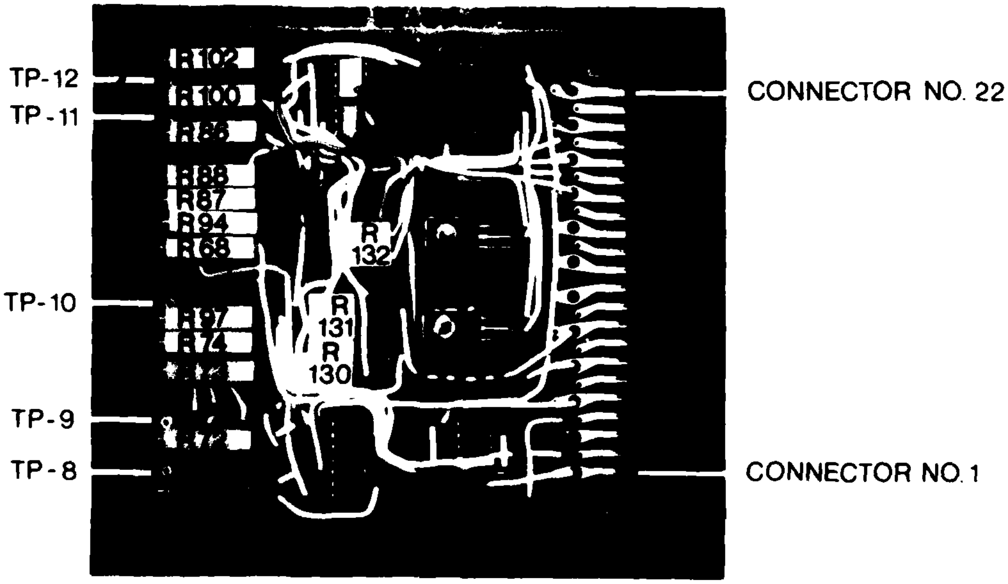

Figure 9 - Photograph of Card No. 1

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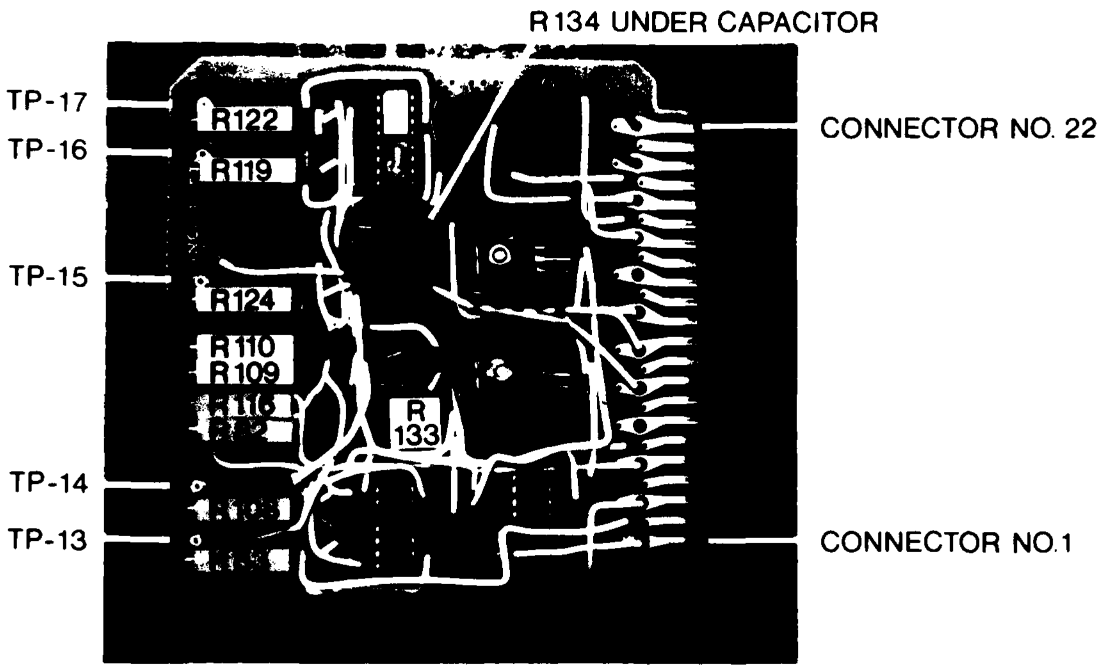

Figure 10 - Photograph of Card No. 2

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TABLE 1 - ADAPTIVE CONTROL CIRCUIT TEST VOLTAGES

Input (volts)	TP-1 (volts)	TP-3 (volts)	TP-4 (volts)	TP-5 (volts)	TP-6 (volts)	TP-7 (volts)
±0.030	+0.313	+0.183	-1.010	-9.860	-13.059	+0.636
	-0.316	+0.175	-1.005	-9.791	-13.059	-0.625
±0.060	+0.614	+0.371	-1.254	-8.164	-10.601	+1.224
	-0.602	+0.356	-1.201	-7.795	-10.587	-1.232
±0.150	+1.523	+0.970	-3.258	-3.021	-3.955	+1.181
	-1.550	+0.935	-3.154	-2.921	-3.950	-1.151
±0.300	+3.101	+2.004	-6.704	-1.456	-1.905	+1.173
	-3.156	+1.938	-6.490	-1.408	-1.902	-1.151
±0.500	+5.157	+3.330	-11.149	-0.870	-1.138	+1.178
	-5.202	+3.219	-10.785	-0.840	-1.136	-1.148

TABLE 2 - LISTING OF RECOMMENDED ELECTRONIC TEST EQUIPMENT

1. Sinusoidal signal generator

   0.05 Hz - 0.20 Hz; 0.100 VDC - 5.000 VDC

2. Precision voltage source

   0.000 VDC - 10.000 VDC by 0.001 VDC

3. Digital volt meter 4-1/2 digit

4. Frequency counter

   0.050 Hz - 0.200 Hz by 0.0005 Hz

5. Rate table (used only to calibrate rate sensor)

   0.5 degree/second - 10.0 degree/second

6. Extender card for cinch connector No. 250-22-30-170

7. Oscilloscope

TABLE 3 - ACTUATOR PARTS LIST

1. 90° ELL; Parker Hannifin #4-4CBTX-SS
2. ¼ D.D. x .031 WALL SEAMLESS STAINLESS STEEL TUBE
3. MOOG VALVE, #62-105
4. MOOG VALVE MANIFOLD, NSRDC Dwg. #E15-3467-7 Piece No. 1, Aluminum
5. UNION TEE; Parker Hannifin #4-JBTX-SS
6. TEE, HYDRAULIC; Parker Hannifin #¼-MMS-SS
7. STRAIGHT; Parker Hannifin #4-4FBTX-SS
8. 90° ELL; Parker Hannifin #¼ x ¼-CD
9. SLIDING CYLINDER SHAFT PAD, NSRDC Dwg. #E15-3467-4 Piece No. 7, 6061-T6 Aluminum
10. 4-40 x 3/8 ALLEN HEAD CAP SCREWS
11. ROTATIONAL FEEDBACK POT CLAMP, NSRDC Dwg. #E15-3467-4 Piece No. 10, Aluminum
12. RADIAL ARM FEEDBACK POT; Vernitron Corp., Deerpark, NY #8213
13. 8-32 LOCKNUT
14. 8-32 THREADED-ROD
15. FEEDBACK POT STAND-OFF TUBE, NSRDC Dwg. #E15-3467-7 Piece No. 5, Stainless Steel
16. RADIAL ARM FEEDBACK POT MOUNTING PLAT, NSRDC Dwg. #E15-3467-5 Piece No. 7, 6061-T6 Aluminum
17. 4-40 LOCKNUTS
18. PORT SIDE PLATE, NSRDC Dwg. #E15-3467-6 Piece No. 4, 6061-T6 Aluminum
19. GUSSET, TOP, NSRDC Dwg. #E15-3467-6 Piece No. 1, 6061-T6 Aluminum
20. SHIP LINKAGE ROD TO CLUTCH JAW, NSRDC Dwg. #E15-3467-5 Piece No. 8, 6061-T6 Aluminum
21. ¼-28 UNF HIME LOCKNUT (jamnut)
22. ¼" HIME ROD END; HIME #HM-4
23. GUSSET, AFT, NSRDC Dwg. #E15-3467-6 Piece No. 2, 6061-T6 Aluminum
24. RRS SYSTEM CLUTCH FORK, NSRDC Dwg. #E15-3467-7 Piece No. 3
25. MANIFOLD; Parker Hannifin #4MD-IM-400-S-10
26. CYLINDER CONTROL VALVE; Parker Hannifin #3MD-20-AG-10
27. ¼-20 NYLOC NUT
28. BOLT KIT; Parker Hannifin #51-BK-4MD-A
29. ROTAC, Ex-Cello Corp., Greenville, OH #S-250-1V
30. STBD. SIDE PLATE, NSRDC Dwg. #E15-3467-6 Piece No. 3, 6061-T6 Aluminum

TABLE 3 (Continued)

31. ¼-20 x 2½ BOLT

32. 10-24 x ½ PHILIPS HEAD MACHINE SCREW

33. ELECTRICAL CONNECTOR, GSA #5935-00-815-0514

34. ¼-20 x 1½ BOLT

35. CLUTCHJAW, STARBOARD, NSRDC Dwg. #E15-3467-4 Piece No. 2, 304 Stainless Steel

36. ¼ FLAT WASHER

37. CLUTCH SLIDE-ROD FORK, NSRDC Dwg. #E15-3467-5 Piece No. 10, Mild Steel

38. PUMP STROKE RATE LEVER, NSRDC Dwg. #E15-3467-5 Piece No. 1 Mild Steel

39. ¼-20 x 1" BOLT

40. SLIDING CYLINDER ROTATIONAL CONTROL ROD, NSRDC Dwg. #E15-3467-5 Piece No. 3, 304 Stainless Steel

41. RETAINER ROLL PIN, ¼" DIA. x 1¼", NSRDC Dwg. #E15-3467-5 Piece No. 9, Steel

42. SLIDING CYLINDER, NSRDC Dwg. #E15-3467-4 Piece No. 3, Bronze

43. COTTER PIN, 3/32 O.D. x 1" 1

44. RETAINER PIN, NSRDC Dwg. #E15-3467-5 Piece No. 4, 304 Stainless Steel

45. CLUTCH YOKE; NSRDC Dwg. #E15-3467-4 Piece No. 6, Mild Steel

46. YOKE CONTROL FORK ARM, NSRDC Dwg. #E15-3467-7 Piece No. 2, Mild Steel

47. 5/16 - 18 UNC JAMNUT

48. CLUTCH PIVOT STAND-OFF, NSRDC Dwg. #E15-3467-5 Piece No. 2, Brass, ½ O.D. x .125 wall tube

49. ¼-20 THREADED ROD

50. HYDRAULIC CYLINDER, LINEAR, #1 in.-BB-2A14x 3/4 in.

51. HYDRAULIC CYLINDER MOUNTING ASSEMBLY; Parker Hannifin #74076

52. RADIAL ARM, NSRDC Dwg. #E15-3467-6 Piece No. 5, Mild Steel

53. RRS SYSTEM CLUTCH FORK EXTENDER, NSRDC Dwg. #E15-3467-5 Piece No. 5, 6061-T6 Aluminum

54. 10-24 x 3/8 SET SCREW, ALLEN

55. CYLINDER STAND-OFF, ½" O.D. x .125 wall brass tube

56. SLIDING CYLINDER-CLUTCH SHAFT, NSRDC Dwg. #E15-3467-4 Piece No. 4

57. CLUTCH JAW, PORT, NSRDC Dwg. #E15-3467-4 Piece No. 1, 304 Stainless Steel

58. ¼-20 x 2" BOLT

APPENDIX A
THEORY OF OPERATION

Before beginning the process of application in the physical world, it is of interest to define the theory of operation. Quite simply, we are endeavoring to use the roll moment developed by offsetting the rudder to oppose the roll moment induced by the seaway. That is, when the ship tends to roll to port due to seaway, we will use a rudder offset which tends to roll the ship to starboard. Perfection is achieved when the two oppositely directed tendencies to roll are equal, resulting in no rolling motion. Obviously, the direction, displacement, and phasing of the rudder movements determine how effectively we are using the stabilizing moment available to us from the rudder. The signal which controls the rudder movement is generated within the controller unit of the rudder roll stabilization system.

Ideally, the rudder control system would be required to produce a rudder angle command signal which produces the maximum possible roll reduction at all frequencies. This could, in principle, be attained by having the command signal phased so that the rudder moment opposes the wave excitation moment for all frequencies. This ideal control, designated as "opposed control" by Conolly,[1] may be represented by

$$\delta = K_1\phi + K_2\dot{\phi} + K_3\ddot{\phi} \qquad \text{(A1)}$$

where the values of the individual control gains are related as

$$\frac{K_1}{K_3} = \omega_\phi{}^2, \; \frac{K_2}{K_3} = 2n\omega_\phi \qquad \text{(A2)}$$

where δ = rudder angle

ϕ = roll angle

$\dot{\phi}$ = roll velocity or roll rate

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[1] Conolly, J.E., "Rolling and Its Stabilization by Active Fins," Trans. RINA, Vol. 111 (1969).

$\ddot{\phi}$ = roll acceleration

K_1 = roll angle gain

K_2 = roll rate gain

K_3 = roll acceleration gain

ω_ϕ = ship natural roll frequency

n = roll decay coefficient

The $K_1\phi$ portion of the command signal is in phase with roll; whereas the $K_2\dot{\phi}$ component of the command signal leads roll by 90 degrees, and the $K_3\ddot{\phi}$ leads roll by 180 degrees. Thus increasing the K_2 and K_3 portions of the rudder command signal increases the phase angle by which the command signal leads roll angle. At roll resonance under opposed control, the $K_1\phi$ and $K_3\ddot{\phi}$ terms cancel such that the rudder command signal generated by this control law produces a rudder moment (movement) which leads roll by 90 degrees, i.e., the rudder command signal consists entirely of the $K_2\dot{\phi}$ term. At frequencies above resonance, the phase angle by which the ideal rudder moment leads roll increases. Thus, the relative importance of the roll acceleration component of the command signal increases above resonance. Below resonance, the phase angle by which the ideal rudder moment leads roll decreases. Thus, the importance of the roll component $K_1\phi$ of the command signal increases as frequency decreases below resonance. In fact, at zero frequency the phase angle is zero, and the entire rudder command signal is thus composed of the roll signal term.

To overcome the practical deficiencies of opposed control, alternate control laws are generally used. These alternate laws relax the amount of roll reduction required for nonresonant rolling. Since we are primarily interested in showing feasibility, we will initially investigate a control signal of the form

$$\delta = K_2\dot{\phi} \qquad \text{(A3)}$$

which is termed velocity control and is a more than adequate starting point. Using this control equation, rudder movements will occur with a frequency approximating the natural roll frequency. Velocity control functions most effectively at resonance where it is identical to opposed

control, with the rudder moment leading roll by 90 degrees. Thus, like opposed control, velocity control functions most effectively for ships with narrow banded roll responses. Therefore, it is expected that feasibility can be shown using velocity control. Once feasibility has been demonstrated, the control equation may be modified, if desired, to provide additional stabilization by including the $K_1\phi$ and $K_3\ddot{\phi}$ terms.

Some idea of the rudder movements under the direction of these two control signals may be gained from our experience on ships at sea. At headings forward of beam seas, the ship will tend to roll at a frequency close to its natural roll frequency while at headings aft of beam seas it will tend to roll with a somewhat lower frequency due to broaching and surfing tendencies. Thus, using a velocity control law at relative headings from head to beam, the rudder will tend to oscillate at the natural roll period with excursions dependent on the values of K_2 and the roll rate. At headings aft of beam seas, the rudder will not oscillate as quickly due to the slower polarity change in roll rate. For a given value of K_2 the rudder excursion in quartering and following seas will be less than in beam or bow seas if the roll angles experienced are comparable. This is found to be caused by the lower value of roll rate since the same angular change over a longer time period yields a lower rate of change. Note that this correctly implies that velocity control will not tend to correct a constant heel angle since the roll rate is zero.

The rudder excursion will generally increase with increasing roll angles since the roll rate increases. At first glance this appears to be a favorable phenomenon; specifically, the rudder excursions increase with increasing roll angles thereby generating more stabilizing moment when it is most desired. This would indeed be desirable if the rudder were capable of meeting the demand for larger and larger excursions. Since the roll period will generally be near resonance and does not significantly increase or decrease with roll angle, the rudder is required to move at increasingly rapid rates in order to execute these larger and larger excursions. There comes a point at which the rudder cannot move rapidly enough to perform as directed by the control law. This point marks the beginning of rate saturation and results in rudder excursions which are not properly phased. Stabilization degrades rapidly and destabilization may occur.

Since rate saturation is highly undesirable, one is tempted to predict the maximum value of roll rate which is likely to be encountered and select a K_2 value which will ensure that the rudder rate required by the control law is always less than that available. This method is straightforward; however, it results in rudder excursions which are small in all but extreme conditions and therefore produces small rudder moments in all but extreme conditions.

Rudder moments near the maximum available from the steering system demand the rudder excursions remain near the maximum allowable without inducing rate saturation. This criteria is met by the real time computation of a K_2 value which, based on the recent time history of roll rate, will allow rate saturation less than one excursion in ten. The mathematical derivation of K_2 is as follows.

Since roll angle ϕ and its derivatives can be considered a stationary random process, and

$$\delta = K_2\dot{\phi} \tag{A4}$$

where δ = rudder angle

$\dot{\phi}$ = roll rate

K_2 = control constant

It follows that the oscillatory rudder angle (and its derivatives) used to reduce roll motion is also such a process. Hence, using the relationship

$$\text{Probability } (F > \pm F_{LIMIT}) = 1 - \text{erf}(F_{LIMIT}/\sqrt{2}\, F_{RMS})$$

$$\dot{\delta} = 0.606|\dot{\delta}|_{LIMIT} \tag{A5}$$

and

$$\dot{\phi}_{RMS} = 1.48\, E(|\dot{\phi}|) \tag{A6}$$

where $\dot{\delta}$ = rudder rate

$|\dot{\delta}|_{LIMIT}$ = absolute value of maximum rudder rate available (4.67 deg/sec w/two pumps)

$\dot{\phi}_{RMS}$ = root mean square of roll rate

$E(|\dot{\phi}|)$ = expected absolute value of roll rate, i.e.,

Probability $\{|\dot{\phi}| > E(|\dot{\phi}|)\} = 0.50$

The latter expression being employed to simplify the requirements of the physical computation circuitry.

Making the further assumption that roll motion is a narrow banded process,

$$\ddot{\phi}_{RMS} \approx \omega_\phi \, \dot{\phi}_{RMS} \tag{A7}$$

and hence using equations (A5), (A6), and (A7) in

$$\dot{\delta}_{RMS} = K_2 \, \ddot{\phi}_{RMS} \tag{A8}$$

$$K_2 = \frac{0.41|\dot{\delta}|_{LIMIT}}{\omega_\phi \, E(|\dot{\phi}|)} \tag{A9}$$

Thus by accepting the available rudder rate as $\dot{\delta}_{LIMIT}$, knowing the natural period of the vessel, and computing $E(|\dot{\phi}|)$ real time; a K_2 value which adapts to the prevailing conditions to yield large rudder excursions and yet not allow unacceptable levels of rate saturation is found. The adaptive circuit within the processor generates a control signal based on this process, thus,

$$\delta = K_2\dot{\phi} = \left\{\frac{0.41 \; \dot{\delta}_{LIMIT}}{\omega_o \; E(|\dot{\phi}|)}\right\} \dot{\phi} \tag{A10}$$

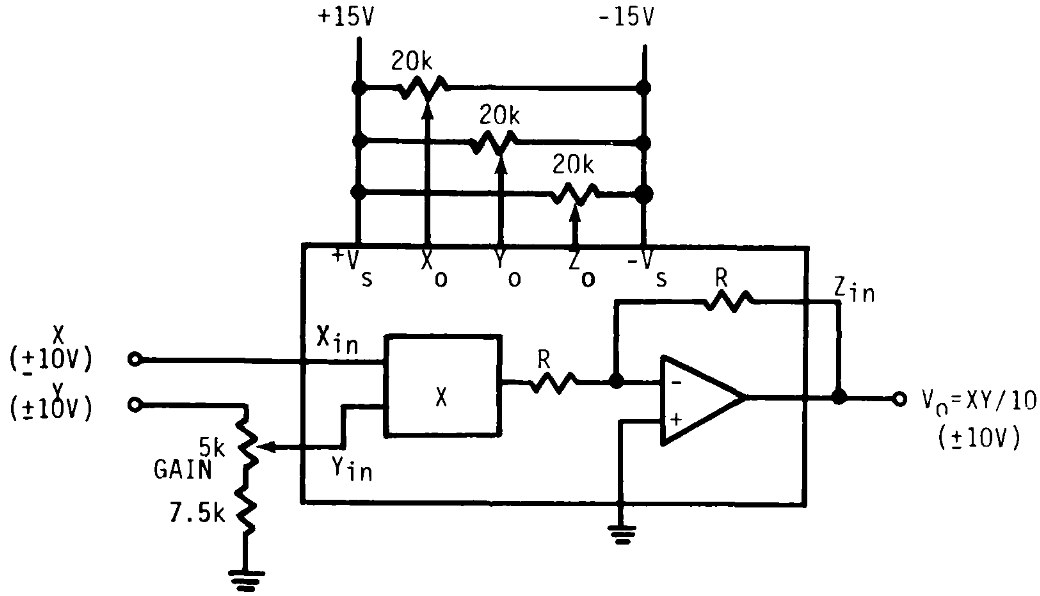
Assuming two pump operation and a 10.8 second natural roll period, this law for the WHEC HAMILTON Class becomes,

$$\delta = 3.29 \; \dot{\phi}/E(|\dot{\phi}|) \tag{A11}$$

APPENDIX B
AD 533 TECHNICAL INFORMATION

MULTIPLIER

Multiplier operation is accomplished by closing the loop around the internal op amp with the Z input connected to the output. The X_o null pot balances the X input channel to minimize Y feedthrough and similarly the Y_o pot minimizes the X feedthrough. The Z_o pot nulls the output op amp offset voltage and the gain pot sets the full scale output level.



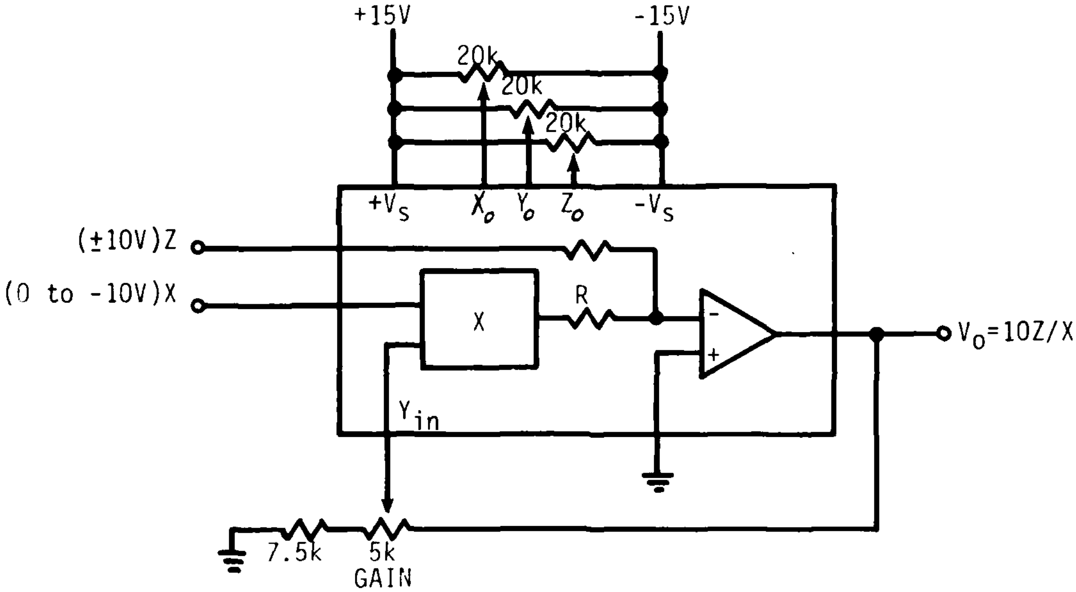
TRIM PROCEDURES

1. With X = Y = 0 volts, adjust Z_o for OVDC output.
2. With Y = 20 volts p-p (at f = 50Hz) and X = OV, adjust X_o for minimum ac output.
3. With X = 20 volts p-p (at f = 50Hz) and Y = OV, adjust Y_o for minimum ac output.
4. Readjust Z_o for OVDC output.
5. With X = +10VDC and Y = 20 volts p-p (at f ≈ 50Hz), adjust gain for output = Y_{in}.

NOTE: For best accuracy over limited voltage ranges (e.g., ±5V), gain and feedthrough adjustments should be optimized with the inputs in the desired range, as linearity is considerably better over smaller ranges of input.

DIVIDER

The divide mode utilizes the multiplier in a fed-back configuration where the Y input now controls the feedback factor. With X = full scale, the gain (V_o/Z) becomes unity after trimming. Reducing the X input reduces the feedback around the op amp by a like amount, thereby increasing the gain. This reciprocal relationship forms the basis of the divide mode. Accuracy and bandwidth decrease as the denominator decreases.



TRIM PROCEDURES

1. Set all pots at mid-scale.
2. With Z = 0V, trim Z_o to hold the output constant, as X is varied from -10VDC through -1VDC.
3. With Z = 0V, X = -10VDC, trim Y_o for 0VDC.
4. With Z = X or -X, trim X_o for the minimum worst-case variation as X is varied from -10VDC to -1VDC.
5. Repeat steps 2 and 3 if step 4 required a large initial adjustment.
6. With Z = X or -X, trim the gain for the closest average approach to ±10VDC output as X is varied from -10VDC to -3VDC.

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